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GEOPHYSICAL RESEARCH PAPERS

No. 4

EVALUATION OF RESULTS OF JOINT AIR FORCE - WEATHER BUREAU CLOUD SEEDING TRIALS CONDUCTED DURING WINTER AND SPRING 1949

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CHARLES E ANDERSON

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Base Directorate for Geophysical Research
Air Force Cambridge Research Laboratories
Cambridge, Massachusetts

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ABSTRACT

The question of the modification of natural clouds by artificial seeding is examined in terms of current theoretical considerations as to the physical-chemical and meteorological effect of seeding agents on clouds. The results of experimental laboratory studies made in this country and abroad on the formation of the ice phase and precipitation are reviewed. The results of the joint Air Force-Weather Bureau seeding trials then are studied in light of these theoretical considerations. The combined theory and experiments point to little likelihood of large-scale weather control using present techniques.

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EVALUATION OF RESULTS OF JOINT AIR FORCE - WEATHER BUREAU CLOUD SEEDING TRIALS CONDUCTED DURING WINTER AND SPRING 1949*

1. INTRODUCTION

Although the discovery of the nucleating properties of solid carbon dioxide and silver iodide has been relatively recent (1946, 1947), many seeding trials already have been conducted in this country and other parts of the world with varying results. A number of reports concerning these trials are available. They form a bibliography extensive enough to enable unacquainted persons to review the essentials of the present hypotheses and the practical results achieved. (See Bibliography.)

Perhaps the most significant feature exhibited by this literature is the apparent lack of quantitative treatment of observed results in terms of present theories. This lack is undoubtedly due to the limitations of the existing theories and to the difficulty of measuring the magnitude of changes produced in those meteorological factors which are thought to be influential insofar as obvious results are concerned.

As a direct consequence, assumptions and rough estimations are required in any attempt to account for the observed phenomena or to predict future cloud behavior induced by artificial seeding.

*Manuscript received for publication 28 Mar 1950

Sufficient observational information has been collected, however, to substantiate the following reliable conclusions regarding cloud seeding as now being practiced.

(1) An inherently thermodynamically unstable cloud (one containing supercooled water drops) can be induced to undergo a change in physical state (liquid drops to ice particles) by seeding.

(2) The formation of precipitation, the growth, or the dissipation of a cloud are secondary phenomena resulting in part from the presence of ice crystals being formed within the cloud but not solely dependent upon this requirement. In other words, the extent to which a given modification is manifested is related directly to the physical as well as the thermodynamic state of the subject cloud.

(3) The environment in which the subject cloud is located may have great influence on the subsequent changes in cloud structure, and thus must be taken into account.

Since the secondary effects are precisely the ones of military or economic interest, the most serious problem confronting experimentalists in this field

is to determine those optimum conditions (cloud character and environment) which will yield these secondary effects.

This problem may be attacked by a statistical analysis of the results of indiscriminate seeding trials under a variety of conditions; or an effort can be made to determine the optimum conditions through theoretical extension of the known facts, followed by verification trials.

Unfortunately, the accumulated data concerning the physical and thermodynamic characteristics of clouds are too incomplete to permit a rigorous application of the latter approach. As pointed out earlier, the deductions would be, by necessity, very qualitative. A similar situation would be encountered in a thorough analysis of already conducted seeding trials. The majority of these experiments show a consistent lack of measurement of those cloud parameters which are necessary to define the physical and thermodynamic state of the cloud. As a result of this lack of quantitative data, dependable conclusions as to the specific requirements for optimum seeding conditions never have been established.

2. THEORETICAL CONSIDERATIONS

2.1 DIRECT EFFECT OF CARBON DIOXIDE ON CLOUD

2.11 *Formation of Ice Crystals*

In the course of a systematic search for materials which would serve as sublimitation nuclei, Schaefer[1] discovered that any object whose temperature was below a critical limit (-38.9°C, according to Schaefer) would induce the formation of ice crystals in a cloud previously composed of supercooled water droplets. This temperature dependence for the crystal formation has been substantiated by workers in other countries, although there remains some question about the numerical value of the critical temperature. In Great Britain, Cwilong[8] and later D'Albe[3] report that this threshold temperature is at -41°C. In contrast in Germany Findeisen and Schulz[4] found that small numbers of ice crystals formed at temperatures as high as -13°C, but that the number increased greatly at temperatures below -32°C. Vonnegut[1] discovered that silver iodide would initiate the formation of ice crystals at temperatures as high as -6°C, but the number formed per unit volume was inversely proportional to the temperature.

The phase transitions observed in the above experiments have raised many interesting questions concerning the nature of the nuclei effecting the change and the exact mechanism whereby the conversion is brought about.

Although these points have not been explored in great detail as yet, it has been demonstrated amply that artificial seeding agents will produce large numbers of ice particles in supercooled clouds. Solid carbon dioxide, liquid air, or any substance whose temperature is sufficiently low, are efficient in this respect.[1,5] In the case of silver iodide, cadmium iodide[3] or volcanic ash,[1] one is led to suspect that these materials act as artificial nuclei for either freezing of supercooled water, or as direct sublimation of water vapor. These later materials, however, apparently are not as efficient as the low-temperature method for the production of ice particles.

2.111 Number of crystals formed.--The important question here is not whether ice particles can be produced in a supercooled cloud, but how many can be produced. Specifically, how does this quantity vary with temperature, cloud characteristics and seeding agent? Unfortunately the available information will not permit a precise answer to this question. Langmuir,[6] by using assumptions, calculated the number of ice nuclei generated by various sized pellets of carbon dioxide falling through air at -20°C. He determined that approximately 10^{13} nuclei per cm^3 are activated. A 1-cm pellet produces 10^{17} nuclei of approximately 10^{-6} cm diameter during its fall. The paper presenting these calculations is brief and does not show how these values were computed. Palmer,[2] D'Albe,[3] Findeisen,[4] and Schaefer[1] have made estimates of the number of ice nuclei observed when the temperature of a supercooled water cloud is lowered. A fair agreement exists among these various authors regarding the temperature region where a marked increase in the number of ice particles occurs. Findeisen found this temperature to be about -32°C. Cwilong and D'Albe give -41°C as the critical temperature, while Schaefer and coworkers believe the transition range to be at -38.9°C.

According to Schaefer, the ice nuclei (tiny ice crystals) form spontaneously in a supercooled cloud whenever the temperature falls below the critical value of -38.9°C. It could be argued that this transformation is a manifestation of the selfnucleation mechanism brought about by density fluctuations in the vapor. Findeisen and coworkers feel that the mechanism is one of activating already-present foreign bodies to serve either as freezing nuclei for liquid water or sublimation nuclei for water vapor.

If one accepts the latter argument and also assumes that the activity of the nuclei is related inversely to the temperature and that this relationship holds to very low temperatures, a comparison of the observed results reported by several authors (Fig. 1) with Langmuir's calculated value (10^{13} nuclei per cm^3) indicates a possible consistency. The observations of Palmer definitely show a linear relation between the log of nuclei number and

temperature. The nuclei number per unit volume as given by Langmuir would agree with the values extrapolated from Palmer's data provided the cooling action of the carbon dioxide pellets would be sufficient to reduce the temperature of the affected air to -80°C (Fig. 1).

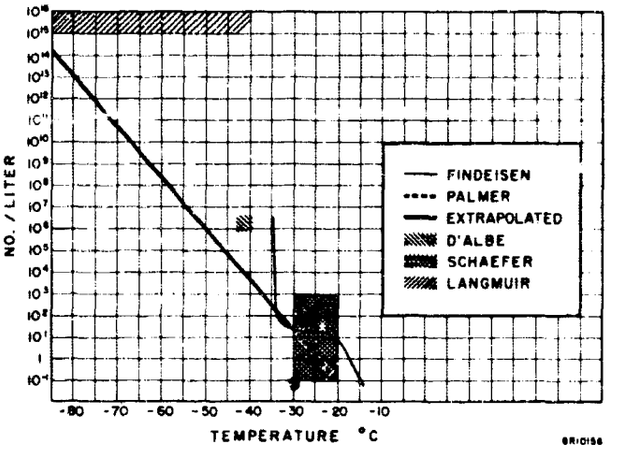

Fig. 1. Ice nuclei concentration as a function of temperature (as reported by various authors).

Objections immediately can be raised against this concept of the nucleation mechanism even after allowing for the qualitativeness of the extrapolation. The cooling action of the carbon dioxide pellet may be sufficient to reduce the temperature of the affected air to such a low temperature. However, if this reduction were accomplished, it would be for only a brief interval; the majority of the activated nuclei would return to a neutral state as soon as the heat exchange between the boundary layer and the ambient air caused an increase in nuclei temperature. Of course those nuclei fortunate enough to begin rapid growth would survive, but their number would be relatively few. A more serious objection is the apparent decrease in activity of nuclei below 210°K reported by Dobson[7] and Cwilong.[8] Hence, an extrapolation of Palmer's observations to these low temperatures is not likely to be valid. Furthermore, if these nuclei are foreign particles of dust, the number required by Langmuir exceeds the observed number of dust particles by a factor of 10^{10} or more.

A spontaneous nucleation of supersaturated vapor induced by extreme cooling would not require the presence of foreign dust, and the number of nuclei would depend only on the thermodynamic characteristics of the system. Fisher et al[9] have shown that such a process is possible in a supercooled liquid, and have calculated its rate. D'Albe,[3] however, found that for thoroughly cleaned air only two ice crystals per cubic centimeter appeared at temperatures in the neighborhood of -41°C and at a relative humidity of 108 percent over water. This experiment, considered independently, does not suggest a natural formation of ice particles by spontaneous nucleation. It may be, nevertheless, that the extreme local cooling due to the carbon dioxide is sufficient to cause supersaturations great enough for a high rate of spontaneous nucleation to proceed.

The only sources for making estimates of the number of ice nuclei which can be formed by reducing the temperature of water vapor are the aforementioned papers. The values range from 10^3 particles per

cm^3, as observed in experimental chambers, to 10^{13} particles per cm^3, as computed theoretically by Langmuir. It might be advantageous to inspect data from the observation of natural ice clouds to arrive at a better estimate. Kuettner[10] reports that natural ice-particle concentration seldom exceeds 10^4 to 6×10^4 particles per m^3. Palmer[2] states that the number of ice particles required for steady, widespread rain, if it is assumed that each raindrop originates as an ice particle, is of the order of 10 particles per liter. The concentration required for instability rain is only 1 per liter.

These concentrations are considerably lower than either the experimental or theoretical values previously stated, but it must be remembered that every snowflake does not have to become a raindrop, nor does every raindrop formed at altitude reach the ground.

2.112 Type of crystal formed.-- Of equal importance to the number of ice nuclei formed is the type of ice crystals formed when a supercooled cloud is seeded with solid carbon dioxide. On review of the papers treating the various forms of natural ice particles, it is seen that the temperature and relative humidity of the environment are the decisive factors which determine the macroscopic shape of the ice crystal. Wall[11] gives an excellent summary on this question and includes results of personal observation of supercooled fogs. In the temperature range -2° to -7°C ice needles were predominate; -8 to -10°C, plate forms; -12° to -18°C, skeleton stars and various dendritic forms; -18° to -25°C double plates, small plates and prisms; and finally for the range -25° to -30°C, prismatic forms. Weickmann[12] made observations of crystal forms from an aircraft; his results substantiate, in general, those of Wall. For over a 15-year period Nakaya and coworkers[13] have investigated the growth and forms of ice crystals artificially created in the laboratory. They have succeeded in producing as infinite a variety of ice crystals as is found anywhere in the atmosphere, by varying the conditions of temperature and saturation. There appears to be no connection between the type of starting nucleus and the final form, since Nakaya[14] demonstrated very convincingly that a transition of one form into another can be effected by simply varying the environmental conditions. Vonnegut[1] also remarked on the tremendous influence of the environment when he noticed that small traces of butyl alcohol vapor would modify the observed ice-crystal shape from plates to prisms. This effect was unchanged when the nucleating agent was changed from silver iodide to carbon dioxide. It therefore seems safe to conclude that the kinds of ice crystals produced by seeding with carbon dioxide are dependent on the thermodynamic state of the cloud at the time of their formation.

2.113 Summary.--At this point it would be well to summarize the principal *direct* effect of solid carbon dioxide on

supercooled clouds.

(1) Solid carbon dioxide particles act to produce ice crystals in supercooled clouds provided the temperature of the cloud area is a few degrees below freezing (-6°C or lower).

(2) The mechanism whereby the phase transition is accomplished is believed to be one that stems from the low temperatures induced by the solid carbon dioxide. The detailed steps of the transition are not known.

(3) Until the mechanism of the transition is fully understood, a definite estimate of the number of ice nuclei generated by the carbon dioxide cannot be made. At present, two alternative estimates are available: (1) assuming spontaneous nucleation, Langmuir finds an average of 10^{15} nuclei per cm^3 are produced by carbon dioxide pellets ranging from 0.02 to 2 cm in diameter; (2) if it is assumed that the nucleation is produced by natural nuclei which are activated by the low temperature, the number of particles per cm^3 would appear to have an upper limit between 10^2 and 10^4.

(4) The type of ice crystal formed in a cloud is dependent on the environment in which the nucleus or the growing crystal finds itself.

2.12 Density and Temperature Changes

Other direct effects produced by seeding which must be considered are those of density and temperature changes in the cloud.

It has been estimated[1,15] that the conversion of a water-droplet cloud into one composed of ice crystals will be accompanied by an increase in temperature of approximately 1°C. This temperature rise is brought about by the release of the latent heat of fusion (1) when liquid water becomes ice, and (2) when water vapor condenses directly to ice, which would take place since the equilibrium saturation vapor pressure is less over ice than over water.

The cooling effect of solid or gaseous carbon dioxide at approximately -80°C, however, has not been considered. The latent heat of sublimation of carbon dioxide at -78.5°C amounts to 138.48 cal per gram. According to Langmuir[6] a 2-cm diameter carbon dioxide pellet will cool 200 cm^3 of air for each second of fall. Using Langmuir's Eq. (1) for the rate of evaporation of spheres of volatile materials, one can compute the rate of change of mass for the pellet. Solving for the temperature change which this volume of air undergoes in furnishing the necessary heat for sublimation of the carbon dioxide, one finds a reduction of temperature amounting to -8°C for a cloud at -20°C and 500 millibars pressure.

A further local cooling of the cloud will occur, since the carbon dioxide gas initially will have a temperature of -78.5°C. No attempt was made to calculate the magnitude of this latter effect, since it was realized that the temperature decrease would be of a transitory nature unless more than 3 or 4 pounds of dry ice per mile were dispersed into the cloud.

In addition, since the carbon dioxide gas would diffuse freely into the air, it is impossible to set any boundary conditions which would satisfy the actual conditions and permit a calculation of the temperature change due to cooling. It is a certainty, however, that at some short interval of time following the passage of the carbon dioxide pellet through a portion of the cloud, a temperature lowering occurs. It is entirely possible that this temperature decrease is sufficient to cancel out the increase caused by conversion of water drops to ice particles, and in some instances that it is large enough to cause an over-all reduction of temperature in the affected portion of the cloud. If this reduction should take place, a subsidence of the affected portion should take place because of an increase in density. On the other hand, if no appreciable cooling occurs when carbon dioxide is introduced into a cloud, but there is an actual increase in temperature of 1°C, Langmuir[1] believes that this is sufficient to set up local connective action, which spreads the ice nuclei throughout the cloud.

2.2 INDIRECT EFFECTS OF CARBON DIOXIDE ON CLOUD

Among the phenomena ascribed to seeding supercooled clouds with carbon dioxide are precipitation, dissipation, and infrequently the formation of new clouds. It will be interesting to examine each of these phenomenon, using the available observational and theoretical information, to ascertain to what extent they can be promoted by seeding. Again one is faced with the difficulty of trying to determine the influence of a local change on processes which in their natural occurrence are not understood thoroughly.

2.21 Cloud Dissipation

For a water cloud to be visible as such, the cloud-drop sizes must be above a critical size limit since the perceptibility is directly related to the light-scattering properties of the particles. In the mean, this limiting size can be taken at 1 micron. A cloud of particles above this size will appear to the observer as cloud, while one of particles below this size gives the impression of haze or dust.

The dissipation of a cloud, therefore, means the disappearance of most of the drops above the critical size. Disappearance of such drops can be effected in two ways: (1) by reduction of the diameter of the drops or (2) by precipitation. Since the radius of cloud drops ranges between 1 and 100 microns, the fall velocities of the drops (1.26×10^{-2} to 1.26×10^{2} cm per sec) are not sufficient to result in appreciable precipitation. Evaporation of cloud drops is, evidently, the only means of cloud dissipation.

Those processes which are believed responsible for evaporation of cloud particles are (1) mixing with drier air and (2) heating by subsidence or adiabatic compression. Evaporation by mixing with drier air continually occurs at the

boundaries of the cloud. Another example is the dissipation of low-lying, early-morning stratus and fog by turbulent transport into regions of drier air. Whenever a parcel of moist air subsides, it undergoes a compressional heating, since the atmospheric pressure decreases with height. This fact is illustrated by the dissipation of clouds in the lee of mountains whenever the flow is directed downwards. Radiational cooling of clouds, especially in the upper portions, will lead to an increase in density and a subsequent compressional heating attended by evaporation.

It is clear, then, that the promotion of cloud dissipation by carbon dioxide seeding can be stimulated only through the two main processes discussed above. The release of additional heat by the conversion of a water cloud into an ice cloud would be the only mechanism whereby large-scale mixing could be attributed to the seeding. The generation of downward-directed air currents or subsidence could be promoted by carbon dioxide seeding if an increase in the density of the cloud were effected.

2.22 *Formation of New Clouds*

The formation of new cloud elements connotes an increase in the size of drops above the critical limit. Formation of cloud in air previously cloud-free has been mentioned in only one instance.[8] In that case the cloud was thin and very faint, bearing a resemblance to the common convection vapor trail. This formation can be brought about by carbon dioxide seeding if the air layer already has moisture values approaching saturation so that an induced cooling is sufficient to institute water or ice-particle formation and growth. This type of phenomenon is unimportant since it can be induced but rarely. Those cases, however, where a greatly increased growth was reported in an already present cloud (cumulus type)[1,16] are extremely important. To achieve an increase in the size of a cloud by seeding with carbon dioxide, a potentially unstable thermodynamic condition must be present, which is then triggered by seeding, thereby leading to the release of heat and the development of large-scale convection. The fact that seeding can accomplish such results has not been demonstrated convincingly.

2.23 *Precipitation*

Perhaps the most important--and certainly the most controversial--effect ascribed to seeding is that of stimulating precipitation from supercooled clouds.

Precipitation may be defined as falling hydrometeors (rain or snow) which reach the ground. Those precipitation elements which fail to reach the surface are described as virga. In terms of amount per time interval, precipitation can be classified as to its intensity. Thus, light rain corresponds to an intensity of fall between 0.005 inch per hr or less (a trace) and 0.10 inch per hr; moderate rain, between 0.11 inch per hr and 0.30 inch per hr; and heavy rain, to intensities exceeding 0.30 inch per hr. All rain

is characterized by drops of a size range between 0.5 mm (500 microns) and an upper limit somewhere between 5 and 9 mm, depending upon the nature of the airflow past the drop. From observations of precipitation it has been found that light rain has a maximum drop-size frequency of 0.5 mm or below; moderate rain has a maximum size frequency between 0.5 and 1.00 mm; and heavy rain has a maximum frequency of 1.0 mm, with secondary maxima between 1.0 and 2.5 mm.[17]

The primary problem regarding the origin of precipitation is one of formulating mechanisms whereby cloud drops with maximum diameters in the mean lying around 50 microns can grow into raindrops. The average cloud-drop diameters are much smaller (between 5 and 25 microns), thus making the problem still more difficult.

In an effort to account for the transition of cloud elements into precipitation elements, two theories have been advanced in recent years.

The first theory was the Bergeron-Findeisen theory, which states that all rain above drizzle intensity originates through an ice particle stage. Because of a vapor pressure difference between ice and liquid water (amounting to a maximum of 0.27 mb at -12°C) an evaporation of liquid water drops to the vapor state, and a subsequent condensation of this water vapor directly to ice, occurs when ice particles and water drops coexist in a cloud. In this manner, an ice nucleus can grow to a large ice particle having a considerable falling speed. The ice particle melts after it has passed through the freezing level, and appears as rain at the surface.

The second theory was advanced recently by Langmuir.[6] By deriving equations for the rate of growth of drops by accretion, he shows that moderate-to-heavy rain may originate by a chain-reaction mechanism in clouds at temperatures above freezing. He feels that when drops above a critical size are introduced into cumulus-type clouds, accretion may lead to large, unstable drops. These drops, by virtue of their instability, then break up into two or more droplets. The fragments are able to grow by accretion into unstable sizes, and breakup again occurs. A chain reaction thus ensues, and a thick cloud with a large water content yields a considerable amount of rain.

Since the production of a mixed cloud (one in which ice particles and water drops coexist) is a result of carbon dioxide seeding, rain stimulated in such a manner is looked upon as verification of the Bergeron-Findeisen theory.

2.231 Colloidal instaoility.--The Bergeron-Findeisen theory is by no means a detailed or well integrated set of hypotheses integrating a large number of observed facts; it is merely a framework for an explanation of precipitation. Within this general framework many details are hazy and subject to speculation. Essentially, the theory considers the influence of colloidal instability on a cloud. If this condition is imposed on a

cloud, the differences in fall velocity for different-size cloud elements leads to accretion, and possibly precipitation. Findeisen maintained that sufficient colloidal instability leading to a high degree of accretion could be realized only in the mixed cloud. As mentioned before, here the ice particles can grow at the detriment of cloud drops by direct sublimation, and thus increase the colloidal instability. This growth leads to large-size ice crystals which have high rates of fall. On falling, accretion occurs and the ice particle is covered with water drops which freeze to its surface. This form is called graupel and is believed to be the source of all moderate-to-heavy precipitation. After the graupel passes through the freezing level, it melts and becomes a large raindrop.

It is evident that this precipitation theory is still incomplete; it is especially lacking in experimental verification for many of its essential details. One can estimate, however, the order of magnitude of various effects by using the results of other investigations and applying them to this general theory.

If raindrop formation is in accordance with colloidal instability theory, one then is interested in the growth possibilities for a water drop or ice particle by (1) condensation-evaporation and (2) accretion.

2.232 Raindrop formation by condensation-evaporation.--Expressions for the rate of growth or evaporation of a spherical liquid droplet in contact with its vapor have been derived by Langmuir[6] and others.[18] Comparison of the various derivations indicate they all are based on the assumption that the rate of growth or evaporation is proportional to the vapor density gradient in the ambient air surrounding the droplet and can be expressed in terms of a modification of Fick's law for diffusion.

By using the equation presented by Langmuir[6] for the rate of gain or loss of mass, curves can be plotted relating the vapor pressure gradient and the amount of growth after an interval of time:

$$Q = \frac{4\pi MDr\,\Delta p}{RT}, \qquad (1)$$

where

Q = rate of gain or loss of mass,

M = molecular weight of liquid,

D = diffusion coefficient of vapor through air,

Δp = difference in vapor pressure between drop and ambient air,

R = gas constant, 8.3×10^7 erg per mole per degree,

T = absolute temperature.

Equation (1) can be integrated to get an expression involving the dimensions of the droplet, shown by

$$t = (r^2 - r_0^2)\,RTS/2MD\Delta p, \qquad (2)$$

where

t = time in seconds,

r = radius at time t,

r_0 = radius at time t_0,

s = density of liquid.

In general, for initial radii below 1 micron the term involving r_0^2 can be neglected, and Eq. (2) reduces to

$$t = r^2 RTS/2MD\Delta p . \qquad (3)$$

The equation was evaluated for air temperature of $+5^{\circ}C$ and three values of vapor pressure gradient. These results are shown in Fig. 2, where the log of the drop radius is plotted against the log of the time for the three values of Δp. Curve A is for $\Delta p = 1.12$ mm. This case corresponds to a situation where drops of different temperatures are brought adjacent to one another as described by S. Pettersen and Bergeron.[19] In this case the temperature difference is assumed to be $2^{\circ}C$. Curve B is for $\Delta p = 0.30$ mb, corresponding to the maximum vapor-pressure difference between ice and water which is believed responsible for the growth of ice particles at the expense of supercooled droplets. Finally, curve C represents $\Delta p = 0.1066$ mb, which is the difference between the vapor pressure over a 10μ or larger drop and the ambient air possessing a relative humidity of 101.75 percent--the supersaturation necessary to maintain a 0.1μ drop of water in equilibrium with the air. This value was computed by use of the Kelvin equation, which relates the vapor pressure over a curved surface to that of a plane surface. Thermodynamic instability of type A is much more efficient for promoting droplet growth than the other two types, B and C; however, the frequency of occurrence of such a condition required by type A is as yet undetermined.

If one assumes the lower limit of a raindrop size to be 500 microns, the time required for growth according to

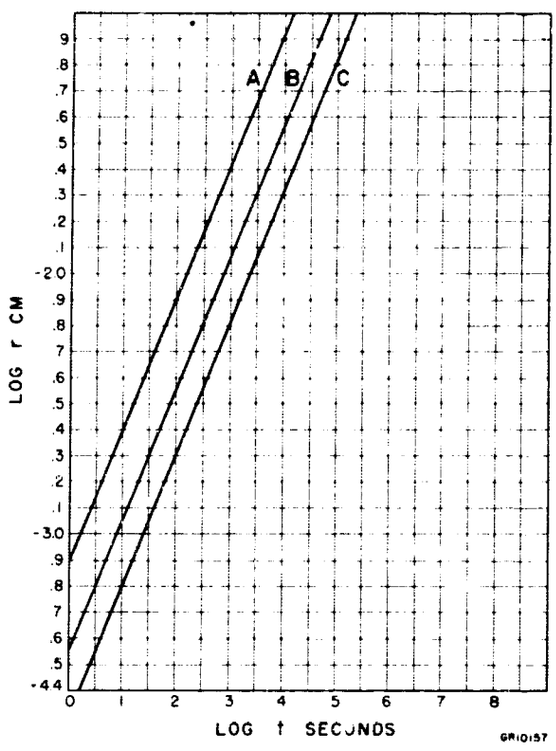

Fig. 2. Time required for water drops to grow to radius γ at different values of vapor pressure difference (temperature = + 5°C).

A is 1.15 hours, to B is 5.8 hours, and to C is 16 hours. It is believed that normal supersaturation in the atmosphere is less than the value given for C. It is highly improbable, therefore, that even small raindrops or drizzledrops will form as a result of condensation alone, in view of the time needed to maintain such high values of supersaturation. This view was advanced at an earlier time by Findeisen,[20] and his values for the growth times agree fairly well with those given above.

Althougn curve B represents the growth of drop according to vapor pressure differences of the same order of magnitude as that between ice and water, the growth of drops can proceed much more quickly. If ice and liquid water coexist, the air is supersaturated with vapor in respect to the ice to an extent depending on the temperature, and thus it is possible for the supersaturation to be much larger than that given by C.

The rate of growth of an ice particle cannot be computed according to the equation used for water droplets, since the shape of an ice particle is not generally spherical. Nakaya[13] measured the rate of growth of various artificially produced snow crystals and reported a growth-rate range of 0.5 to 4.6 mm per hr. This range will yield particles of much greater size than liquid water drops if both are produced as a result of supersaturation. Although the crystals may have a large growth rate, the mass increase is small, since the forms usually are quite flat. Under conditions where snowflakes only are formed, the intensity of the precipitation would be light (less than 0.11 inches per hr). If the freezing level is sufficiently high, the snowflakes can melt, producing light rain consisting of raindrops of 0.2 to 0.5 mm average size. Thus it appears possible that small raindrops can be produced by a condensation-evaporation mechanism, provided ice and water particles coexist in the cloud source.

If the growth of a snowflake or ice particle proceeds as described above, then the amount of growth of a single particle would be dependent on the concentrations of the competing particles in the cloud. Qualitatively, this means that for the same initial supersaturation, maximum growth is achieved with small particle concentrations.

Since the supersaturation in respect to the ice particles is induced by the presence of liquid drops, and since the growth of ice particles is directly related to the supersaturation degree, it would be expected that the final size of an individual particle would be a function of the ratio of the number of ice particles to number of liquid drops. Bergeron[19] feels that optimum growth of ice particles proceeds when this ratio has a value of perhaps 10^{-3}. He feels that exceedingly low concentrations of ice particles, giving ratios of 10^{-6} or less, would lead to big but very sparse precipitation elements. On the other hand, ratios of 1 or greater

would mean that in a short time the cloud would become a pure ice cloud, but that individual ice particles would be too small to cause precipitation. Bergeron classifies ratio values of 10^{-6} or less as *underseeding* and the ratio value of 1 or greater as *overseeding*.

In this connection it is interesting to note that if one assumes the number of ice nuclei generated by carbon dioxide seeding to be of the value given by Langmuir (10^{13} - 10^{17} per cm^3), then, according to Bergeron designation, in every instance of seeding with carbon dioxide a case of *overseeding* results, because the number of drops per cm^3 seldom exceeds 10^3 and on the average is about 10^2. Thus one would think that carbon dioxide is *too efficient* as a seeding agent.

2.233 Raindrop formation by accretion.--The other mechanism believed important for the growth of cloud particles to precipitation elements is that of accretion--particle capture resulting from different-sized particles with different falling speeds (colloidal instability). Langmuir[1] has developed theoretical expressions which enable one to calculate the rate of growth of a spherical collector on falling into a cloud of uniform-sized drops. Several cases have been computed and are plotted in Fig. 3. The abscissa, t, is the time in minutes necessary for a collector of initial radius, S_0, to grow to 3000 microns. The values of S_0 comprise the ordinate. The liquid water content, W, was assumed to be constant throughout the cloud, and for Fig. 3, it was assumed to be 1 gm/m^3. Curves A, B, C, and D represent cloud-drop sizes of 20, 10, 6, and 4 microns, respectively.

Since Langmuir gives a relation between t and W,

$$t = \frac{B}{W}$$

where

B is the integral,

$$B = 4\int_{S_0}^{S_1} \frac{ds}{EU}, \text{ of which}$$

E = collection efficiency,

U = falling speed,

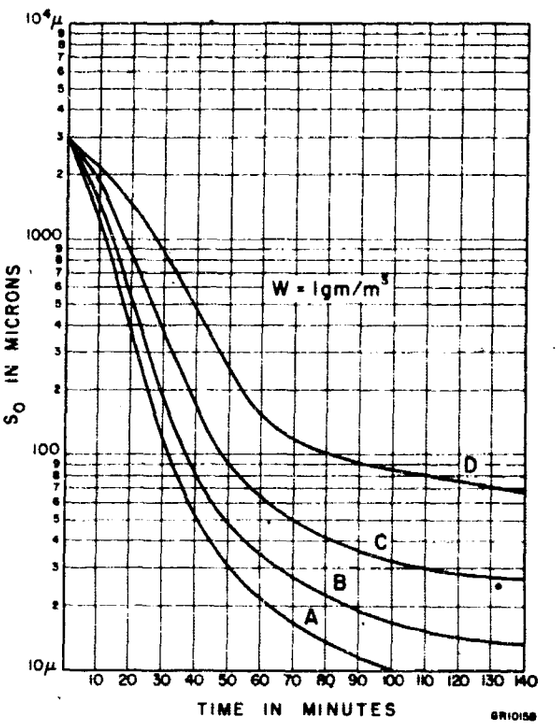

Fig. 3. Time required for collector of initial radius S_0' to grow by accretion to 3000 μ (after Langmuir).

it is quite simple to calculate the time for other values of W. The time necessary for a drop S_0 to grow to a size just below 3 mm can be found quite easily by subtraction on the time axis.

Depending on the size of the uniform cloud drops, there is a critical size of the collector, S critical, below which no collection occurs. Since the critical size varies inversely as the cloud-drop sizes, it is evident that another mechanism must operate to produce the required size if coagulation is to proceed. The only obvious mechanism is that formulated in the previously discussed condensation-evaporation theory. Table 1 has been prepared illustrating the connection between cloud-drop sizes, critical collector size, and time required to reach S critical by condensation alone. The values of the supersaturation given by curve C (Fig. 2) were used to compute the time for condensation growth. The possibility of coagulation in a cloud of uniform drop size below 4 microns appears to be small, according to Table 1. The time required for a drop to grow by condensation to the critical collector size is prohibitive in the case of drops below 4 microns.

It would be interesting now to examine the possibility of raindrop growth of the favored-sized cloud drops. To aid in reaching a decision, Fig. 4 was plotted, showing the relation between the height or distance of fall d, the initial S_0 of the collector, and the radius of the cloud drops r. Inspection of Fig. 3 indicates that for all the values of S given by Table 1 the time required for their growth into 3-mm drops exceeds 140 minutes. This information, coupled with the fall distances shown in Fig. 4, shows that times greater than 2 hours and fall distances longer than 14 kilometers are necessary for even the favored sizes; thus little likelihood for raindrop formation exists in the cases shown in Table 1. However, since the size of the collectors shown in Fig. 1 are the minimum and thus possess low collection efficiencies, larger initial size collectors will be much more efficient. There exists the drawback that

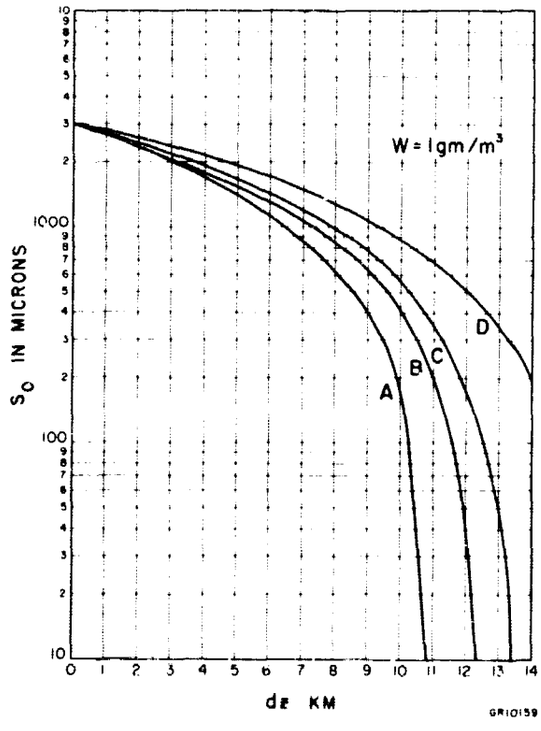

Fig. 4. Distance required for collector of initial radius S_0 to grow to 3000 μ (after Langmuir).

TABLE 1

Relation Between S critical, r, and t (after Langmuir)

r Microns	S critical Microns	$t_{condensation}$ Minutes
1.5	600	1.67×10^3
2.0	350	4.7×10^2
3	140	61
4	58	13.3
5	31	3.74
6	20	1.67
7	14	0.835

the time needed for growth of the initial size by condensation may become quite large. Furthermore, on inspection of Fig. 4, one finds that the only size collectors which have fall distances of less than 10,000 ft are those whose initial radii are above 2000 microns.

These findings show fairly conclusively that raindrop formation from pure water clouds is improbable. Langmuir[1] suggests that raindrop formation from such clouds can occur only when vertical currents are present. These currents, in effect, lengthen the fall path of a droplet if it is borne upward by the vertical current. Findeisen[20] maintained that precipitation above drizzle intensity could not be produced from pure water clouds. The numerous observations of shower-type precipitation from pure water clouds in tropical latitudes indicate, however, that the theory needs modification to include these phenomena.

No attempt has been made to compute the rate of growth of an ice particle by accretion. Preliminary consideration of the problem indicated that it is much more involved than in the case of pure water drop accretion, since the shape and size of the ice particles have a marked influence on the rate of accretion.

2.234 Summary.--Although theoretical substantiation may be lacking, there is enough observational evidence to indicate that graupel particles are primarily responsible for light through heavy rain in temperate latitudes. Theoretical demonstration of the role that graupel assumes in precipitation will have to be along lines developed for raindrop growth in pure water clouds. It must yet be established that a particle having the size, mass, and shape of a small graupel pellet would have a high enough collection efficiency so that growth into raindrop

sizes would be possible within reasonable limits of cloud thickness, liquid water content, and drop size distribution; also, the necessary conditions for the formation of the initial size graupel would need examination to determine under what circumstances one could expect to find these particles.

Observational evidence places the formation of graupel chiefly in the -10° to -12°C range. Speculation might lead one to suspect that the graupel (which is composed of layers of frozen cloud droplets around a central core) is formed from a particular type ice particle. In the temperature range favorable for the appearance of graupel, Wall[11] reports that plate forms are prevalent. Findeisen,[20] however, shows the possibility of graupel formation from stellar-form crystals. Until more experimental and theoretical investigation on the graupel-forming process is carried out, the exact starting form cannot be designated.

It is evident, however, that if one accepts the hypothesis that graupel formation is essential for significant rain intensities, then the thermodynamic state of the cloud has a most important bearing on the results of any particular rain-making attempt. In accordance with the tenets of this graupel theory, one should seed under those conditions most favorable for the formation of graupel if artificial rain is desired.

Known favorable conditions for graupel formation are (1) supercooled clouds with the ice phase present, (2) appreciable convective activity in the cloud, (3) vertical extension of cloud of 10,000 feet or more, and (4) a high liquid water content. Ordinarily, if these essentials are present, rain ensues without the help of artificial seeding. Seeding is valuable in situations where all these conditions are fulfilled except that of the presence of the ice phase.

The circumstances of cloud dissipation and induced precipitation have been discussed in a most general manner. In the following section, these ideas will be examined more closely in connection with the seeding trials conducted by the joint Air Force-United States Weather Bureau Cloud Physics Project during the winter and spring of 1949.

2.3 PHASE III, CALIFORNIA OPERATION

From 1 February to 15 April 1949, nine seeding missions were flown over the western slopes of the Sierra Nevada mountain range. The flights were made within a 100-mile radius of McClellan Air Force Base, generally in the vicinity of Lake Tahoe, Nevada. During these missions, 15 actual seedings were made under various meteorological conditions. Table 2 was compiled by project personnel in the report covering this phase.[21] Of the 15 trials, seven resulted in definite break formation in the seeded area. This is approximately 50 percent success, insofar as formation of breaks is concerned. The mission reports were re-examined and Table 3 was

TABLE 2

Results of Artificial Nucleation of Stratiform Clouds
California Operations
February 15 to April 7, 1949

Observed	No. of Cases	No. of Times Horizontal Divergence Observed	No. of Times Horizontal Convergence Observed	No. of Times Neutral Conditions Observed
*Hole Opened	7	5	0	2
Structural Changes Only	1	1	0	0
No effects Observed	7**	0	3	2

*This category includes cases in which ice crystals remained in the seeded area but separated from the water cloud around the periphery of the seeded areas. In all cases natural dissipation was occurring concurrently.

**Two cases in this category were already ice crystal prior to the seeding run. Horizontal convergence was present in one of these cases, and neutral conditions were present in the other one.

The above calculations of divergence and convergence were made using John C. Bellamy's nomograph, as explained in the February 1949 issue of the *Bulletin of the American Meteorological Society*. Winds near the top of the seeded cloud were used, and they were chosen as near the time of seeding as possible.

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compiled. In those cases where breaks were observed, it is significant that the alto-cumulus decks were less than 1000 feet thick. It would seem that the criteria for hole formation in alto-cumulus cloud decks are as follows: (1) presence of supercooled water cloud only, (2) thickness of deck of less than 1000 feet, and (3) seeding of more than 1 lb per mile.

It is interesting to note that the project personnel felt that dissipation occurred only when natural dissipation was present over the general area. Table 2 shows that in five of the seven reported cases of hole formation, horizontal divergence was present. Thus it appears that hole formation under the influence of seeding only can be accelerated, not initiated.

The California trials were too few to permit final conclusions regarding seeding in orographic clouds, either from the viewpoint of practical results or verification of the cloud physics theories mentioned earlier. However, the results can be examined to determine whether or not the theoretical ideas previously discussed find justification in a general qualitative manner.

Accordingly, in six of the seven cases where hole formation occurred in Table 3, a transition from pure water cloud to one containing ice crystals was definitely confirmed by the optical phenomena observed. Glories always indicate water cloud, while clear icing is indicative of supercooled water cloud. The transition was characterized either by a marked change

TABLE 3

Results of Artificial Nucleation of Stratiform Clouds after Re-examination
California Operations
February 15 to April 7, 1949

Date	Synoptic Weather Prevailing	Type of Seeded Cloud	Thickness Feet	Temp. of Base °C	Temp. of Top °C	Seeding Rate lbs/ mile	Was It Super Cooled Only?	Were Ice Crystals Formed?	Did Ridge First Appear?	Did Breaks Form?
15 Feb	Frontal	Alto cu	800	-6°	-7°	4	yes-glory seen	yes-sun-pillars	yes-slight	yes
1 Mar	Pre-Frontal	Alto cu	700	-11°	-12°	4	?	yes	?	yes
23 Mar #2	Fresh Air Post Frontal	Strato cu	4000	-2°	-8°	2	yes-clear icing glory	?	no	yes
24 Mar										
#1	High	Alto cu	500	-15°	-21°	2	?	yes	no	yes
#2		Alto cu	500	-15°	-21°	1	?	yes	no	yes
#3		Alto cu	500	-15°	-21°	10*	?	yes	no	yes
7 Apr #1	High	Alto cu	3-500	-8°	-10°	1	yes-glory	yes-sun-pillar	no	yes
22 Feb	Pre-Frontal	Alto cu	3000	-1°	-8°	4	yes-glory	?	slight	no
24 Feb	Post-Front-	Alto-								
#1, #2	al Rain	stratus	1000	-4°	-5°	4	?	?	?	?
2 Mar	Frontal-rain	Alto cu	8000	-10°	-27°	4	Nc Rime icing	-	slight	
9 Mar	Frontal-snow	Alto cu	?	?	-10°	5	No sun-spots	-	?	?
23 Mar	Fresh Air	Strato cu								
#1,	Post Frontal	and cu	4000	-2°	-11°	3	yes-glory	no	no	no
#3			4000	-2°	-5°	1	clear ice	no	no	no
7 Apr #2	High	Alto cu	3-500	-8°	-10°	1	yes-glory	no	no	no

*mass drop

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in texture of the cloud or the appearance of sunspots or sun pillars in the cloud tops which indicate the presence of ice crystals.

It was stated in the preceding section that the evidence to date seems to point to the overwhelming influence of the environment on the particular type ice crystal produced. Of the six cases where ice crystals were definitely produced as a result of seeding, only two had optical characteristics which would enable one to deduce the type of ice particles producing the phenomena (flights of 15 February and 7 April). Sunspots or sun pillars were observed in these two cases, and according to Wall[11] this type of phenomenon is produced by plate forms of ice crystals. The temperatures favorable to the appearance of plate forms, as observed by the same author, are -8° to -10°C. Comparison of the reported measured temperatures in the vicinity of the cloud tops where seeding occurred to the critical range agree remarkably well; also, in the one reported instance of sunspots in an unseeded cloud (flight of 9 March), the cloud-top temperature is given as -10°C, which is again in accordance with the required temperature range.

In regard to a scientific explanation as to why dissipation did occur in 7 of the 15 seedings, or conversely, why it did not occur in 8 of the 15 seedings, the limited number of total cases plus the complete lack of cloud variable measurement, create a situation whereby it would be exceedingly foolhardy to claim verification or nonverification of a particular theory.

If one accepts the finding of the project that in the majority of cases where dissipation occurred a natural divergence was present, it is reasonable to consider tentatively that the seeding merely "triggered" a potential downdraft situation.

Turning now to the eight failures insofar as formation of holes is concerned, four of the cases may be discarded immediately, since rain was reported falling from the clouds before seeding was attempted (24 February, and two seedings, 2 and 9 March). The flight of 22 February probably failed because the deck was too thick (3000 ft). The second seeding on 7 April was a failure because too few particles of carbon dioxide were dispersed to render a significant amount of cloud conversion.

Six of the eight failures are now accounted for. The first and third seedings of 23 March are anomalous, since the second seeding produced a hole almost immediately under very similar conditions to the other two. It is noted, however, that the second seeding did not produce observable ice crystals as in the other cases. In this case, the immediate formation of the hole may not be attributable to the seeding.

In none of the seedings was rain formation observed either visually or on the

radar screen. According to the ideas discussed earlier, rain formation would not be expected if the cloud thickness were not greater than about 10,000 ft in the absence of strong vertical currents. Nothing in the reported results indicates that this view is incorrect.

From a practical viewpoint, the results do not have great significance. They show that it may be possible to create holes in supercooled alto-cumulus decks by seeding, provided the decks are thin (less than 1000 ft) and general divergence exists in the region. The possibility of precipitation release from these clouds is non-existent.

These two over-all conclusions would not appear important to military or civil interests.

2.4 PHASE IV, MOBILE OPERATION

On the completion of the California seeding trials, the project shifted to the Gulf of Mexico region, where operations were carried on during the period 1 May to 15 June 1949. The project, based at Brookley Air Force Base, carried out seeding trials on cloud systems over the Gulf up to 100 miles from shore. Seeding trials also were conducted over land in selected regions.

The purpose of the project was to determine the effect of seeding cumuliform-type clouds in semitropical regions. During the period of approximately 1-1/2 months, 13 missions were flown, in which 39 seeding trials were attempted. A statistical breakdown of the missions is shown in Table 4, compiled by project personnel.[22] It immediately appears significant that in 27 of the 39 trials precipitation was reported falling from the cloud after the seeding occurred. In 13 of the 27 cases of precipitation, however, radar echoes were detected from the subject cloud before the seeding was made. The appearance of radar echoes on an APS-10 (3-cm) radar set was an excellent indication of the presence of precipitation. This factor reduced the number of cases where precipitation followed seeding to 14 out of a possible 26, or slightly more than 50 percent. In only one seeding (third trial, 27 May) was the supposedly dry-ice-induced precipitation of greater intensity than virga.

Twelve trials resulted in no observation of any type precipitation. Examination of the mission reports and Table 4 leads to acceptable explanations in some of the cases. In three instances (third seeding, 9 May; second and third seedings, 5 June) the cloud may not have been supercooled, since the free air temperatures reported were -3° and -2°C, respectively. Eight of the 12 unsuccessful trials (in respect to formation of precipitation) were characterized by the use of stagnant or dissipating cumulus cloud as the test cloud. Little precipitation would be expected under these conditions if the criteria outlined in the preceding section was observed. The four remaining unsuccessful trials were re-examined and the following comments were noted for these missions:

(1) *Second Seeding (23 May 1949)* The top of the cloud separated from the base and dissipated at the seeding level.

TABLE 4

Results of Artificial Nucleation of Cumuliform Clouds

Mobile Operations

1 May to 15 June 1949

Date	Base of Clouds	Top of Seeded Cloud	Temp. Vicinity of Bases	Temp. Vicinity of Tops	Est.APOB Freezing Level of Environment	Seeding Altitude	Were Clouds Supercooled?	Were Ice Crystals Observed?	Pounds CO_2 per Mile	Was There Partial Dissipation Only?	Was There Complete Dissipation?	Was There Only Building after Seeding?	Status of Cloud B - Bldg.; D-Depg; S - Stg.	Was There Cloud Echo before Seeding	Was There Cloud Echo after Seeding?	Was Light Rain Falling before or after Seeding without Echo?	Did Rain Fall From Cloud?	Amount of Rain	Were There Natural Showers within 30 Miles?
5-9-49	5600	16000	13	-5	12800	14900	Yes	Yes	5	Yes	No	No	B	No	Yes	No	Yes	Virga	Yes
5-9-49	5600	17000	13	-8	12800	15500	Yes	No	5	Yes	No	No	B	Yes	Yes?	No	Yes	T	Yes
5-9-49	5500	15000	13	-3	12800	15000	Yes?	?	5	Yes	No	No	S	No	No	No	No	None	Yes
5-18-49	4000	17500	18	-6	14200	16100	Yes	Yes	5	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
5-23-49	4500	18500	16	-10	13900	17000	Yes	No	5	Yes	No	No	S	No	No	No	No	None	Yes
5-23-49	4500	18000	16	-8	13900	16500	Yes	Yes	5	Yes	No	No	B	No	No	No	No	None	Yes
5-23-49	4500	16900	16	-7	13900	16800	Yes	?	4	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
5-23-49	4500	18000	16	-8	13900	17000	Yes	No	4	Yes	No	No	S	No	No	No	No	None	Yes
5-23-49	4500	16000	16	-5	13900	15700	Yes	No	4	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
5-24-49	3000	16600	20	-5	13700	17200	Yes?	?	5	Yes	No	No	B	Yes	Yes	No	Yes	Virga	Yes
5-24-49	3000	18000	20	-9	13700	17200	Yes	No	5	Yes	No	No	B	No	No	No	No	None	Yes
5-24-49	3000	18000	20	-9	13700	17100	Yes	No	5	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
5-27-49	5500	19000	15	-9	12300	17600	Yes	No	5	Yes	No	No	S	No	No	No	No	None	Yes
5-27-49	5500	17500	15	-8	12300	18100	Yes?	No	5	Yes	No	No	D	No	No	No	No	None	Yes
5-27-49	5500	25000	15	-25	12300	18000	Yes	Yes	5	Yes	No	No	B	No	Yes	No	Yes	#	Yes
5-27-49	5500	20000	15	-11	12300	18000	Yes	No	5	Yes	No	No	B	No	No	No	No	None	Yes
5-27-49	5500	19000	15	-9	12300	18500	Yes	No	5	Yes	No	No	D	No	No	No	No	None	Yes
6-1-49	4000	14900	21	-2	13700	14800	Yes	Yes	5	No	Yes	No	B	Yes	Yes	No	Yes	#	Yes
6-1-49	4000	16500	21	-4	13700	15000	Yes	Yes	5	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
6-1-49	4000	18000	21	-6	13700	15500	Yes	Yes	20#**	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
6-5-49	5600	15000	16	-2	13600	15000	Yes	Yes	5	Yes	No	No	B	No	Yes	No	Yes	Virga	Yes
6-5-49	5600	15000	16	-2	13600	15000	Yes	No	4	Yes	No	No	D	No	No	No	No	None	Yes
6-5-49	5600	15000	16	-2	13600	15000	Yes	No	4	Yes	No	No	D	No	No	No	No	None	Yes
6-5-49	5600	17000	16	-4	13600	17000	Yes	Yes	5	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
6-5-49	5600	18000	16	-6	13600	17000	Yes	Yes	5	Yes	No	No	B	No	Yes	No	Yes	T?	Yes
6-6-49	5000	20000	18	-10	13700	18080	Yes	Yes	5	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
6-6-49	5000	18000	18	-7	13700	18500	Yes?	?	4	Yes	No	No	B	No	No	A	Yes	Virga	Yes
6-6-49	5000	17000	18	-5	13700	16400	Yes	No	5	Yes	No	No	B	No	No	A	Yes	Virga	Yes
6-7-49	5000	22000	17	-16	12800	19520	Yes	Yes	5	Yes	No	No	D	No	Yes	No	Yes	Virga	Yes
6-7-49	5000	22000	17	-16	12800	19450	Yes	Yes	5	Yes	No	No	D	Yes	Yes	No	Yes	Virga	Yes
6-7-49	5000	24000	17	-25	12800	19400	Yes	No	5	Yes	No	No	B	No	Yes	No	Yes	Virga	Yes
6-8-49	3500	25000	21	-25	13400	20200	Yes	Yes	5	Yes	No	No	B	Unk	*	*	Yes?	#	Yes
6-8-49	3500	22000	21	-15	13400	20500	Yes	No	5	Yes	No	No	B	Unk	*	*	Yes	Virga	Yes
6-8-49	3500	19000	21	-10	13400	19000	Yes?	?	5	Yes	No	No	D	No	No	No	No	None	Yes
6-9-49	2500	17900	22	-7	13500	17490	Yes	No	5	Yes	No	No	B	No	Yes	No	Yes	Virga	Yes
6-10-49	1500	20000	25	-9	14600	17560	Yes	Yes	5	Yes	No	No	B	Yes	Yes	No	Yes	#	Yes
6-10-49	1500	17500	25	-6	14600	17500	Yes	No	4	Yes	No	No	B	No	Yes	No	Yes	Virga	Yes
6-13-49	2500	18000	22	-6	13900	18480	Yes?	?	5	Yes	No	No	B	No	No	A	Yes	Virga	Yes
6-13-49	2500	19500	22	-8	13900	18480	Yes	Yes	5	Yes	No	No	B	No	No	A	Yes	Virga	Yes

* No Radar Observations

Small Shower Reached the Ground--No Rain Gage in Proper Location

** Instantaneous Drop

(2) *Second Seeding (24 May 1949)* Results were confused, since cloud merged with other cloud.

(3) *First Seeding (27 May 1949)* An extract from the mission report is given below: "A building cumulus was seeded on first run. The top was slow in responding to the seeding but it finally changed texture and dissipated. A short time later, however, the cloud was regenerated and built to heights greater than that observed on the seeding run. The cloud finally merged with the anvil of a nearby thunderstorm and was lost."

(4) *Fifth Seeding (27 May 1949)* An extract from the mission report follows:

"Following the 5th seeding into a building cumulus, about 75 percent of the cloud was estimated to have dissipated...while the 5th cloud was observed to be dissipating and changing texture after seeding, other clouds close by were observed to continue building; therefore the seeding results may have been significant."

It appears that unobserved precipitation might have fallen on cases 2 and 3, since the seeded clouds merged with neighboring clouds and were lost. The other two cases, 1 and 4, seem to be definite instances of dissipation by the influence of downward-directed currents created by seeding.

3. CONCLUSIONS

In summary, it appears that the chance of initiating precipitation (although virga only) is excellent in building cumulus containing supercooled drops only. The chance of success of partially dissipating the subject cloud would seem even greater, since this condition ensued in 100 percent of the trials.

The significance of these conclusions insofar as civil or military application is concerned is open to question. The initiation of heavy precipitation from bulging cumulus clouds, by using the techniques employed by the project, does not appear possible. Less interesting is the partial dissipation of cumulus cloud, although it may be possible to inhibit the growth of incipient thunderstorms through such a process. This possibility, however, was not demonstrated by the project.

Regarding the substantiation of any of the theoretical ideas advanced in the preceding sections, there is little information of the proper nature, and even this is not to be considered very reliable. For example, the reported temperatures are those made in free air near the cloud and corrected for dynamic heating. It is obvious that these temperatures can not be employed critically to specify cloud temperatures at the seeding level.

Furthermore, it must be remembered that

the project was not organized, constituted, nor directed to carry out a scientific investigation of cloud seeding. Its purpose was to determine in the way of general, large-scale results the effect of seeding clouds with dry ice.

Thus one must distinguish between success and failure as applied to proposed hypotheses and to obvious results. It is here that the chief difficulty arises in evaluating the success or failure of a particular group of seeding trials.

In the case of outward or general results, a clear decision can be made in a straightforward manner. It is easy to judge the seeding trials of Phases III and IV to be failures with respect to the stimulation of heavy precipitation which reached the earth. It also can be concluded that the production of holes in stratified cloud decks was partially successful provided certain conditions were met.

If one is interested, however, in why a particular trial succeeded or failed, then an acceptable scientific theory must be resorted to for an explanation. In the event that the accepted theory is lacking, it must be developed before much progress will be made in this field.

The nature of the trials conducted to date were not of the type to permit extensive deduction of possible or probable cloud physics reactions resulting from seeding; in addition, acceptable theories are still in an undeveloped state. These are the difficulties that exist at the present time.

It would be a serious mistake to discard completely the concept of cloud modification by artificial means because of the failure to achieve more spectacular results to date. The demonstrated modifications are highly significant in the sense that they prove that cloud control is not an impossibility; and, in fact, it may possibly develop into an extremely valuable technique.

The feeling here, however, is that the greatest need at present is to understand thoroughly the cloud physics processes which are significant in weather control. A sound knowledge of these fundamentals certainly will enable one to make definite predictions as to the extent of possible control, and at the same time point out the direction to which the maximum effort should be made to achieve this control.

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